DOI: https://doi.org/10.15407/pmach2021.04.038

UDC 621.165.5

PRINCIPAL MODERNIZATION SOLUTIONS FOR A 300 MW POWER UNIT TO BE CONVERTED TO OPERATE AT ULTRA-SUPERCRITICAL STEAM PARAMETERS

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This paper analyses the state of power engineering in Ukraine and the main trends in the development of the world market in the field of converting high-capacity powerful power units of thermal power plants into ultra-supercritical(USC) ones. It is shown that the energy sector of Ukraine requires special attention and the introduction of new modern technical solutions. Worldwide trends indicate that the emphasis is now on increasing the steam parameters before a turbine to ultra-supercritical ones. This allows one both to increase the efficiency of power units and to reduce thermal emissions, fighting the global environmental problem of climate warming. The implementation of this approach is proposed taking into account the realities of the Ukrainian economy and the available technical capabilities of the power engineering industry. This paper presents the results of variational computational studies of the thermal scheme of the 300 MW power unit of the K-300-23.5 turbine to be converted into a USC one. The problem was solved under the condition of maximizing the preservation of the thermal scheme, increasing the efficiency of the power unit and minimizing capital investments during the modernization of the turbine. It was chosen to preserve the regeneration system, as well as the medium-pressure (MP) and low-pressure (LP) cylinders. Considered and calculated were variants with the addition to the existing turbine of a USC cylinder and the creation of a new high-pressure cylinder (HPC) with insignificant changes in its overall characteristics. The results of computational studies showed that the most rational variant for modernizing the 300 MW turbine plant is the creation of a new HPC designed for operation at USC steam parameters as well as the addition to the IPC of a new cylinder with the purpose of increasing the reheat steam parameters while preserving the regeneration system.

Keywords: *steam turbine cycle, supercritical steam parameters, thermal scheme, power unit, modeling, efficiency, mathematical model, software package, pressure, temperature, modernization, generation.*

Introduction

The modern centralized energy sector of Ukraine includes 14 thermal power plants (TPP) and four nuclear power plants (NPP), which play a major role in generating electrical energy. Currently, a significant part of power generating assets is worn out and ineffective. More than 85% of TPP units have exceeded the limit of physical wear of 200 thousand operating hours, and more than 40 units exceeded the limit of 250–300 thousand hours. Thus, this equipment requires replacement or serious modernization, taking into account modern trends in the improvement of thermodynamic cycles and their elements in the field of turbine construction [1].

One of the most promising areas of such modernization is the introduction of USC power units [2–6]. The feasibility of a gradual transition to such units is currently due to the following circumstances:

– increasing steam parameters is one of the most effective ways to increase the efficiency of TPPs. For Ukraine, where climatic conditions allow maintaining a sufficiently deep vacuum in condensers, the main directions for increasing efficiency are increasing steam parameters and introducing a second reheat. It should also be noted that increasing the parameters has a positive effect regardless of the type of fuel used;

– the transition to USC has a significant effect not only in traditional fuel combustion technologies, but also in all combined steam-gas technologies with a developed steam-turbine part;

– increasing steam parameters allows one to reduce thermal emissions, and is one of the important ways to solve the global environmental problem of climate warming.

Thus, the development of a number of proposals to create thermal schemes for USC turbine plants, taking into account the design and layout of the existing equipment at the operating TPPs of Ukraine, is of particular relevance at the moment. Modernization of the existing power units by converting them into USC ones will increase their efficiency with minimal capital investments.

In this paper, considered as a prototype for the creation of USC power units is the 300 MW turbine unit manufactured by JSC Turboatom. TPP power units using JSC Turboatom-manufactured 300 MW turbines are quite widespread in the near- and far-abroad countries [7]. Therefore, a similar modernization has prospects for use abroad. The results of the researches presented in this paper can be used to develop measures for the modernization or design of turbine plants of a different capacity.

A Brief Analysis of the World Experience of Operating USC Power Units

The history of the development of USC power units is more than 60 years old. It dates back to the creation in the United States of the 325 MW Eddystone-1 power unit with steam parameters of 35.9 MPa, 648 °C and double reheat. The unit was put into operation in 1954.

In 1966, at the Kashirskaya TPP (USSR), they started a pilot operation of Kharkov Turbine Plant-manufactured SKR-100-300 steam turbine with initial parameters of 29.4 MPa, 650 °C with a back pressure of 3.03 MPa [8]. It had operated until the mid-70s. The thermal power engineering of the country had gained a unique experience in dealing with USC parameters. This made it possible to check the operational reliability of the main elements of steam turbine plants, which were made of various austenitic steels and study their temperature regimes. Among the many interesting technical solutions used in the SKR-100-300 turbine, a special place is occupied by the rotor cooling system, the development of which remains a serious problem to this day. The results of the operation of this power unit confirmed the possibility of creating industrial USC power equipment.

The Kawagoe-1 power unit (Japan) with steam parameters of 30.5 MPa, 566 °C / 566 °C / 566 °C became the first new-generation USC power unit. The unit was commissioned at the end of 1988, and on June 30, 1989, after the necessary tests, its commercial operation began. After 3 years, the Kawagoe-2 power unit was put into operation. In July 1992, the 700 MW Hekinen-3 power unit (Japan) with steam parameters of 25 MPa, 538°C / 593°C was tested, and in April 1993 it was put into commercial operation. The development of the turbine used all the achievements in materials science, aerodynamics and technology for the manufacture of power equipment, as well as the results of research on cooling systems at the Wakamatsu unit, which was commissioned in 1968.

Subsequently, in Europe and Japan, new USC power units were put into operation: in 1997–1998, two power units at Convoy TPP (Denmark) with a capacity of 400 MW with parameters of 29 MPa, 582 °C / 580 °C / 580 °C; in 1995, one unit at Lubeck TPP (Germany) with parameters 27.5 MPa, 580 °C / 600 °C; in 1997, one unit at Matsuura TPP with parameters 25.6 MPa, 593 °C / 593 °C / 593 °C.

At present, almost all leading turbine-building companies are creating new-generation USC steam turbines. The feasibility of converting to USC units must be assessed by many factors: efficiency, capital investments, environmental friendliness, operating costs, maneuverability, efficiency at partial loads, etc. All assessments must be done in comparison with alternative plants, for example, steam-gas ones with a circulating layer, and in the case of using natural gas, with utilization steam and gas plants.

The effect of increasing steam parameters is cited in many works. Let us dwell on the data, where this effect is presented in the most visible form (Fig. 1) [9]. It can be seen that at temperatures that have long been mastered in Japan (566 °C / 566 °C), when changing from a pressure of 24.1 to 31 MPa and introducing the second superheat, it is possible to totally save up to ~4% of fuel compared to parameters of 24.1 MPa, 538 °C / 566 °C [10]. The effect will be the same if the initial pressure is kept at 24.1 MPa, but the temperature before the cylinders is raised to 593 °C. The assimilation of new materials and the existing operating experience allow us to move to a temperature of 593 °C today.

These calculated data are fully confirmed by the tests and operating experience of the Kawagoe-1 and Kawagoe-2 power units, where a fuel saving of 5% was achieved compared with conventional power units with supercritical parameters of 24 MPa, 538 °C / 566°C. The increase in the efficiency of a power unit is achieved as a result of the optimization of the thermal scheme, improvement of the main and auxiliary equipment and, mainly, the increase in steam parameters of the before the turbine.

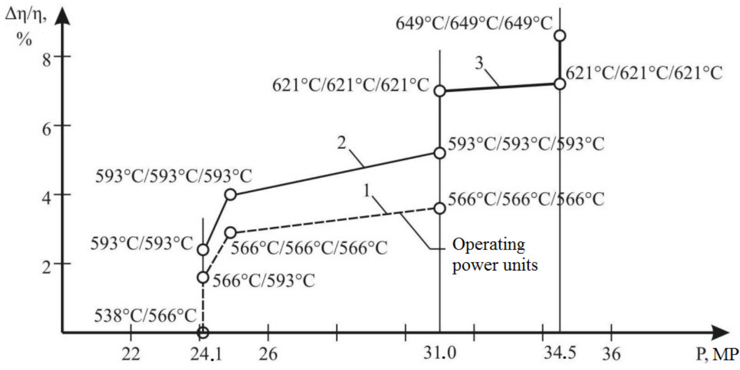

Fig. 1. Relative increase in efficiency in comparison with the efficiency of turbines with parameters 24.1 MPa, 538 °C [9]

Thanks to the increase in efficiency, emissions of harmful substances into the atmosphere, including the greenhouse gas CO_2, are reduced. Today, in the world power industry, the level of steam parameters after the boiler is 30 MPa, from 600 to 620 °C. The efficiency at such units reaches 47% [10].

USC power units operate in Germany, Denmark, Japan, China, Korea, design work is underway in Russia. Currently, in the EU, within the Thermie AD 700 program (AD 700 PF project), a project is being developed to create a USC power unit operating at 35 MPa / 700–720 °C with an efficiency of about 50%. In the USA, Japan, China, and other countries, research has also begun in this direction [11–16]. The declared level of steam parameters requires the use of new materials, namely nickel-based alloys. Taking into account the high cost of these alloys, the increased complexity of the technology of their production and the manufacture of products from them for steam turbine plants, the creation of power units with steam parameters of 32 MPa, 650 °C / 650 °C is considered to be the first stage in mastering USC, which practically does not require the use of expensive alloys [17].

An important issue is the use of the second reheat. The experience of operating the equipment has shown that the use of double reheat at a steam pressure of up to 26 MPa is economically unjustified. The increase in efficiency does not compensate for the complication of the thermal scheme of the power unit, the design of the turbine and the boiler. Therefore, starting from the 80s of the twentieth century, power units with one reheat were mainly built. Only the transition to a higher pressure again makes it advisable to use the second steam reheat.

Increasing the parameters at the turbine inlet significantly affects the design of the flow path. Various approaches can be taken to solve this problem. One of them is the cylinder operation at higher steam parameters without changing the number of stages by using a special design as a high-temperature control stage. This problem was solved for the LMZ K-300-240 serial turbine with an increase in steam parameters to USC ones (29.0 MPa / 580 °C) [9].

In this paper, an alternative approach is considered. It is the addition to the existing 300–325 MW turbines of a USC cylinder or the creation of a new HPC.

Mathematical Model and Algorithm for Calculating Thermal Schemes

The computational studies were carried out using the SCAT software complex, which is the development of the A. N. Podgorny Institute of Mechanical Engineering Problems of the NASU. The basic mathematical model and SCAT software package have been adapted for calculating power plants [18], and verified based on the results of studies of the thermal scheme of high-power combined heat-and-power plants (CHPP). The object of the verification was the T-100/120-130 turbine of power units No. 1 and No. 2 of PJSC "Kharkov CHPP-5" [19–20].

The mathematical model allows us to describe the processes occurring in the elements of an electric power plant by the following equations:

– energy balance for each k-th element of the scheme

$$\sum_{j=1}^{J_k-K_k}(\eta\cdot G\cdot h)_j+\sum_{j=1}^{K_k}(\eta\cdot E)_n=0\,;$$

– the balance of costs for each *l*-th energy carrier of the *k*-th element of the scheme

$$\sum_{j=1}^{J_{kl}} G_j = 0;$$

– hydraulic balance for each *l*-th energy carrier of the *k*-th element of the scheme

$$\left(p_{\text{in}} - \Delta p - p_{\text{out}}\right)_{kl} = 0,$$

– enthalpy changes for each *l*-th energy carrier of the *k*-th element of the scheme

$$\left(h_{\text{in}} - \Delta h - h_{\text{out}}\right)_{kl} = 0,$$

where G, h, p are the consumption, enthalpy and pressure of the energy carrier; E is the energy flow power; η is efficiency; Δh, Δp are the changes in enthalpy and pressure of the energy carrier in the element; J is the total number of energy carriers in the elements; K is the number of energy flows in the elements; indices "in", "out" characterize the parameters at the input and output of the element. Acting as energy carriers in heat and power plants are the streams of water, steam, air, gases, thermal, mechanical and electrical energy. In this case, the flows of heat carriers are characterized by flow rate and two thermodynamic parameters, and the flows of energy, by one parameter – power.

The quantities η, Δh, Δp depend on the flow rate G, and the thermodynamic parameters of the heat carriers X, the design parameters of the elements Z, and for the *k*-th element of the power plant are described as

$$\eta_k = f\left(G_k, X_k, Z_k\right); \quad \Delta p_k = f\left(G_k, Y_k, X_k\right); \quad \Delta h_k = f\left(G_k, Y_k, X_k\right).$$

The consumable, thermodynamic and design parameters of the power plant elements can only change within the physically and technically feasible states of the energy carriers and structures. Therefore, the system of equations is supplemented by a system of constraints

$$G_k^{\min} \le G_k \le G_k^{\max}; \quad Y_k^{\min} \le Y_k \le Y_k^{\max}; \quad X_k^{\min} \le X_k \le X_k^{\max}.$$

Each element of the thermal scheme is considered taking into account heat balances, thermal head, with a number of other parameters, entering and leaving it [21].

The basic thermal scheme of a power plant is presented in the form of separate elements connected with each other by certain signals, as mentioned earlier. Used as connecting signals are energy flows. The calculation of the physical properties of the working medium at certain points is carried out by two-dimensional linear interpolation with the use of the previously calculated tables of the properties of the working medium at the reference nodes.

Modernization of 300 MW Power Units by Their Conversion into USC ones

Based on the foregoing, we will consider the structure of the studies that were carried out to convert the power unit into a USC one.

Two conceptual approaches to the formation of the original thermal scheme were analyzed (Fig. 2, Table 1):

– addition to the existing 300 MW units of an additional USC cylinder;

– replacement of the HPC of an existing turbine with a USC cylinder with a slight change in the size of the foundation.

The calculated studies of the original power unit with the actual state (Fig. 2, Table 1) and during the improvement of the flow path of the HPC, IPC and LPC showed that the gas-dynamic improvement makes it possible to increase the turbine efficiency by 3%, additionally generating 25 MW of electric power without complicating the thermal scheme.

Within the framework of solving the problem of converting the power unit into a USC one under the condition of maximum scheme preservation (Fig. 2), the variant of complete HPC modernization was considered, but with the preservation of the HPC and LPC, as well as the system of the regenerative heating of the feed water of the original unit. The change in the efficiency of the power unit ηi was investigated with varying the initial steam parameters in the ranges t_0=540÷700 °C, P_0=23.5÷35 MPa and pressure in the condenser P_c=3.5 kPa; 6.0 kPa. With that, it was assumed that the steam pressure and temperature at the inlet to the IPC P^{IPC}=3.6 MPa, t^{IPC}=540 °C are constant. The efficiencies of the cylinders were taken to be equal: 90% for the HPC; 94% for the IPC and 87% for the LPC. Main steam flow rate G_0=960 t/h.

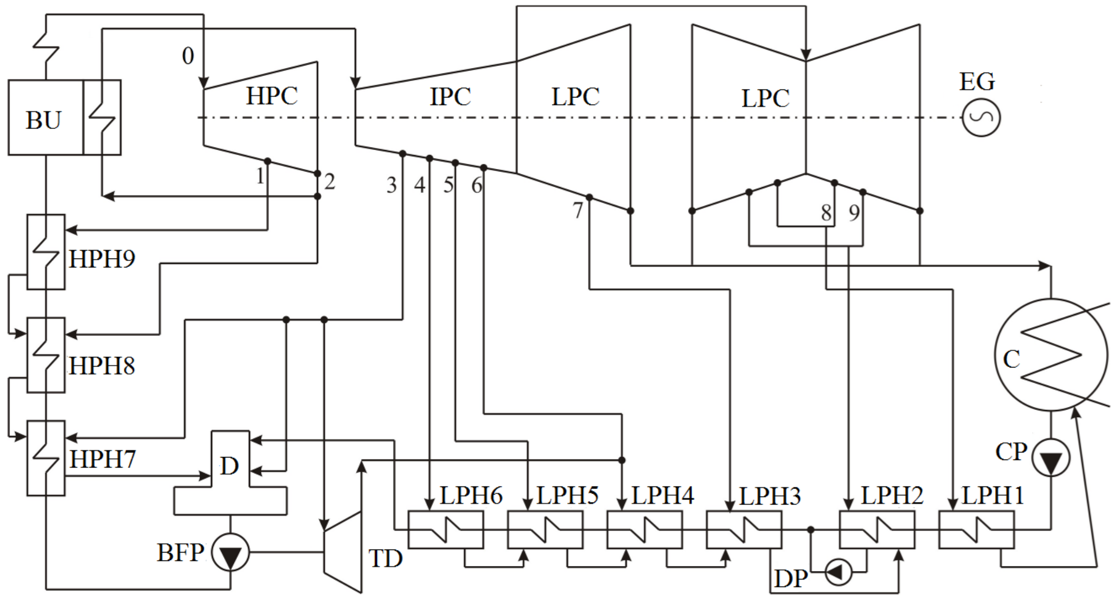

Fig. 2. Thermal scheme of the original 300 MW unit:
BU – boiler unit; HPC, IPC, LPC are high-, medium- and low-pressure cylinders; EG – electric generator; 1–9 – steam extraction; C – condenser; CP – condensation pump; HPH, LPH – high- and low-pressure heater; D – deaerator; FWP – feed water pump; TD – turbo drive; BFP – boiler feed pump; DP – drain pump

Table 1. Parameters of live steam and extractions for the regeneration of the original 300 MW power unit

Parameter name	Steam extraction												
	0	1	2	at IPC inlet	3	TD	D	4	5	6	7	8	9
Pressure P, MPa	23.54	5.691	3.92	3.60	1.50	1.50	1.50	0.604	0.36	0.21	0.118	0.054	0.0137
Temperature t, °C	540	350	310	540	412	412	412	323	262	205	150	90	62

The results of computational studies of such variants are presented in tables 2 and 3 (variant 1 – the original power unit with improved turbine flow path).

In table 2, η_i is the absolute internal efficiency of the turbine unit.

Note that an attempt to simplify the modernization of the power unit by converting it into a USC one while preserving the existing flow path of the HPC (Table 2, variants 5, 8) makes it necessary to significantly increase the pressure before the turbine (for example, at (t_0=700 °C, P_0=53.8 MPa), which significantly increases the auxiliary power consumption of the power unit.

Table 3 shows the results of calculating the thermal scheme with varying t_0=590–700 °C and under the condition of limiting the initial pressure to 35 MPa. This is possible provided the HPC flow path is preserved. As can be seen, the greatest increase in the efficiency of the power plant at t_0=700 °C, P_0=53.8 MPa is ~6.7% (relative), which is in good agreement with the data presented in Fig. 1.

Table 2. Results of computational studies of the conversion of the HPC into a USCHPC while preserving the existing flow path

Parameter name	Parameter variation variants							
	1	2	3	4	5	6	7	8
Amount of heat supplied in the cycle Q_{cy}, MW	732.0	731.9	752.9	775.8	798.1	753.2	776.2	798.3
Pressure before the HPC P_0, MPa	23.54		30.50	41.76	53.80	30.50	41.76	53.80
Temperature before the HPC t_0, °C	540		590	650	700	590	650	700
Turbine inlet pressure P_c, kPa	6.0	3.5				6.0		
Power unit capacity N_{PU}, MW	342.5	351.1	370.2	390.6	409.4	361.5	382.1	400.5
Turbo drive capacity N_{TD}, MW	9.87	9.86	12.60	17.00	21.70	12.60	17.00	21.70
Efficiency η_i, %	46.80	47.97	49.17	50.35	51.30	48.00	49.23	50.17

Table 3. Results of calculating the thermal scheme with varying t_0 (t^{IPC}=540 °C, G_0=960 t/h, P_0<5 MW, P_c=3.5 kPa)

Parameter name	Parameter variation variants								
	1	2	3	4	5	6	7	8	9
Amount of heat supplied in the cycle Q_{cy}, MW	752.9	774.1	790.7	753.6	775.8	792.8	753.5	777.4	795.3
Temperature before the HPC t_0, °C	590	650	700	590	650	700	590	650	700
Power unit capacity N_{PU}, MW	370.0	388.4	402.5	370.7	389.9	404.7	370.7	391.4	407.1
Turbine drive capacity N_{TD}, MW	12.40	12.40	12.40	13.20	13.20	13.20	14.35	14.35	14.35
Power unit capacity less auxiliary power consumption η_i, %	49.14	50.17	50.90	49.19	50.26	51.05	49.20	50.35	51.19

The studies carried out have shown that the parameter significantly effecting the efficiency of the power unit is the initial temperature of the cycle. For example, an increase in the initial temperature for the unit improvement variants under consideration (for example, Table 3, variants 7–9) from 590 to 700 °C leads to an increase in efficiency by ~4% (relative), and an increase in pressure from 30 to 35 MPa at a temperature of 700 °C, only by ~0.6%.

An alternative solution to the problem of converting the power unit into the USC one is the development of scheme designs for the reconstruction of the original power unit. Various variants for the thermal scheme layout were considered (Table 4): a scheme with an additional HPC (AHPC) (Fig. 3); a scheme with an AHPC HPC and two intermediate stream superheating (Fig. 4); a scheme with a modernized HPC (MHPC), intermediate steam superheating and additional IPC (AIPC) (Fig. 5); a scheme with AHPC and an additional HPH (Fig. 6); a scheme with a complete replacement of the HPC with the USCHPC (Fig. 7). The initial steam parameters varied as t_0 from 540 to 700 °C; P_0 from 23.5 to 35 MPa. Steam parameters at the inlet to the original IPC are the following: p^{IPC}=3.6 MPa, t^{IPC}=540 °C. Condenser pressure P_c=6.0 kPa. The results of computational studies are presented in table 3. Scheme variant 1 in table 4 corresponds to the original unit (see Fig. 2).

Table 4. Results of computational studies (t^{IPC}=540 °C)

Parameter name	Scheme variant														
	1	2	3			4			5			6	7		
	Parameter variation variants														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Amount of heat supplied in the cycle Q_{cy}, MW	732.0	752.9	763.3	779.6	783.5	770.3	790.7	799.1	811.1	837.5	848.0	837.7	752.3	766.1	768.6
Pressure before the AHPC/MHPC* P_0, MPa	–	30.93	30/30*										–	–	–
Temperature before the AHPC/MHPC* t_0, °C	–	590		650	680	590	650	680	590*	650*	680*		–	–	–
Steam rate G_0, t/h	960					998	1005	1013	1003			1118	960		
Pressure before the HPC P_0, МПа	23.54								–	–	–	–	30		
Pressure before the AIPC P_0, МПа	–								4.875	6.957	8.252	8.760	–		
Temperature before the AIPC t_0, °C	540		590	650	680	590	650	680	590*	650*	680*	680	590	650	680
Temperature of feed water t_{FW}, °C	260		262	265	267	275	280	285	262	263	264	320	260	265	270
Power unit capacity N_{PU}, MW	342.5	361.4	371.5	387.4	395.0	373.5	391.1	398.4	393.4	419.6	430.4	437.5	360.5	375.8	381.6
Turbine drive capacity N_{TD}, MW	9.87	12.77	12.4	12.4	12.4	12.9	13.0	13.1	12.9	12.9	12.9	14.5	12.4	12.4	12.4
Power unit capacity without auxiliary power consumption η_i, % taken into account	46.8	48.0	48.9	49.7	50.22	48.49	49.46	49.86	48.5	50.1	50.75	52.22	47.92	49.05	49.65

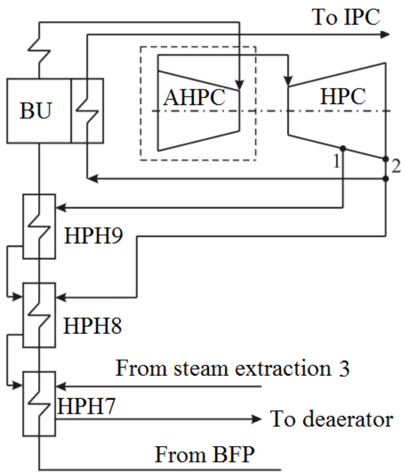

Fig. 3. Thermal scheme with an AHPC (scheme variant 2)

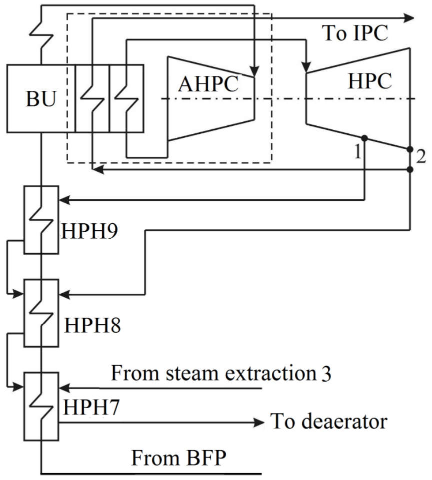

Fig. 4. Thermal circuit with an AHPC and double intermediate steam superheating (scheme variant 3)

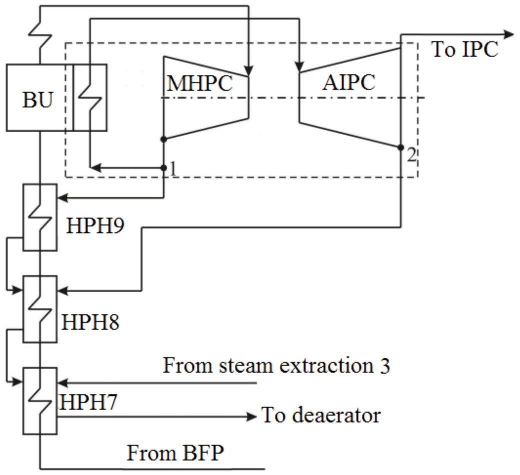

Fig. 5. Thermal scheme with an MHPC and AHPC (scheme variant 5)

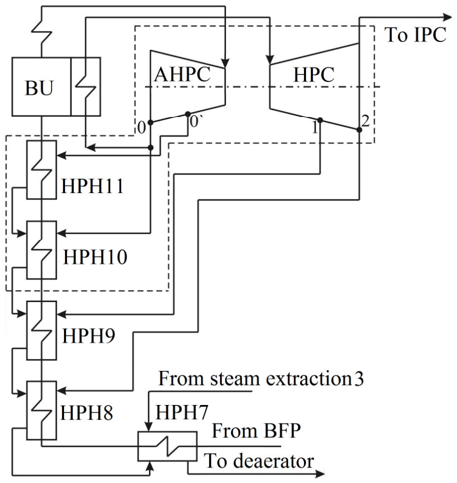

Fig. 6. Thermal scheme with two additional HPHs (variant 6)

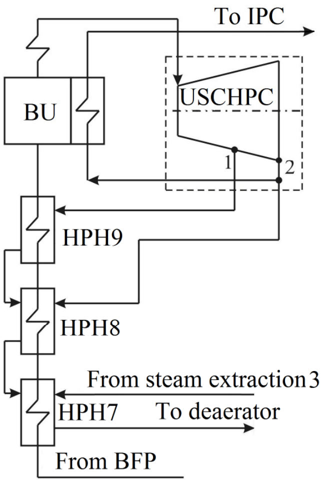

Fig. 7. Thermal scheme with a total replacement of the HPC with a USCHPC (variant 7)

It can be seen that the addition to the original power unit of a USC cylinder with initial parameters P_0=30.5 MPa, t_0=590 °C, on condition that the parameters of the original unit at the HPC inlet (Fig. 3) will provide additional 19 MW of electric power and an increase in the efficiency up to 48%, which is 2.0% (relative) more than the variant after the gas-dynamic improvement of the flow path. However, an increase in the initial pressure leads to an increase in the power of the turbo drive from 10 to 13 MW (Table 4, variant of scheme 2), that is to say, costs of the auxiliary consumption of the unit.

Increasing the initial steam parameters makes the introduction of double reheating of the steam justified. With the change in live steam temperature before the AHPC (590, 650, 680 °C) and a fixed live steam pressure of 30 MPa, the temperature of the first steam reheat varied at the HPC inlet within the rage of 590–680 °C. The steam parameters before the IPC remain unchanged (Fig. 4). This approach makes it possible to obtain additional 10, 26 and 34 MW of energy, respectively, in comparison with the previous variant (Table 4, variant of scheme 3) with an increase in efficiency by 1.5, 3.5 and 4.5%, respectively.

The variant of the reconstruction of the HPC by converting it into a USCHPC and the addition to the IPC of an AIPC (Fig. 5) allows increasing the unit efficiency (Table 4, variant of scheme 5).

A more significant increase in the unit efficiency is achieved through the implementation of the variant with the addition of two HPHs (Fig. 6), which makes it possible to raise the feed water temperature to 320 °C and increase the unit efficiency by ~11% (relative) compared with the original power unit. At the same time, such a thermal scheme becomes much more complicated with a significant increase in auxiliary power consumption (Table 4, scheme variant 6) and therefore will not be considered in the future.

Let us further consider the results of computational studies of the next modernization variant for the unit, namely, the total replacement of the existing HPC with a USCHPC (Fig. 7).

Comparison of the efficiency of this variant (Table 4, scheme variant 7) with the scheme variant 3 with an additional cylinder at P_0=30 MPa, t_0=590, 650, 680 °C showed that in both cases the increase in the efficiency of the turbine unit relative to the original power unit is ~3% (absolute) and ~6–6.5% (relative) at maximum live steam temperature.

For clarity, figure 8 presents the data from table 4 regarding the effectiveness of the considered scheme variants in the form of a generalized diagram. It can be seen that variant 6 has the highest efficiency, however, as indicated above, it requires a serious reconstruction of the regeneration system.

Thus, figure 8 shows that variants 3 (5); 5 (10, 11) can also be distinguished as competing ones.

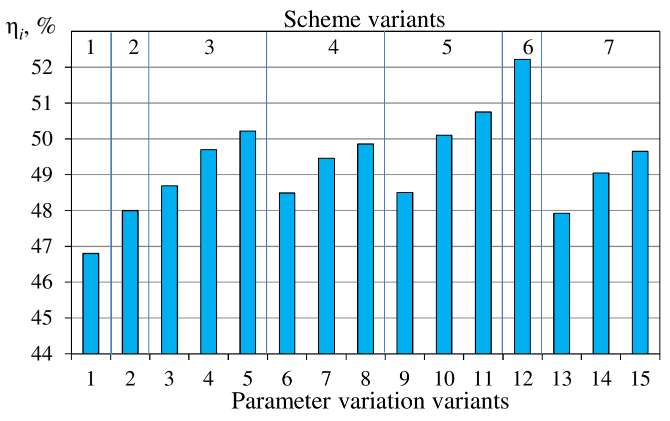

Fig. 8. Change in the power unit efficiency η_i depending on the variant of the scheme

Despite the fact that the efficiency of thermal scheme 5 (11) is 0.65% higher than that in scheme 5 (10) (Fig. 8), when choosing the modernization variant, one should take into account that an increase in the steam temperature above 650 °C leads to the need to use expensive alloys, which significantly increases capital investments in the modernization of the power unit.

Thus, taken as the most rational should be scheme 5 (see Table 4) with the initial steam parameters t_0=650 °C, P_0=30 MPa, which provides for a total replacement of the HPC with an MHPC and the addition of an AIPC to the IPC of the original power unit. The parameters of the steam before the AIPC are t_0=650 °C, P_0=6.957 MPa, and before the IPC they remain unchanged.

For the final approval of such a decision, it is required to carry out a feasibility study, taking into account the necessary changes in regenerative feed water heating system. This is the subject of further research.

Conclusions

1. The performed series of computational studies demonstrates the possibility of converting the existing powerful power units (in particular, 300 MW units produced by JSC "Turboatom") into USC ones, which

will enable to significantly (up to 6–7% (relative)) increase the absolute internal efficiency of the turbine while preserving the designs of the IPC, LPC, as well as the regenerative condensate and feed water heating system.

2. It has been established that the task set can be solved on the basis of the implementation of conceptual approaches to the improvement of thermal schemes:

– addition to existing 300 MW units of USC cylinders;

– replacement of the HPC of a turbine with a USC cylinder.

3. The computational studies have shown that the most significant efficiency increase can be achieved through the use of the scheme variant with an additional USC cylinder and two additional HPHs, which allows us, at the initial parameters t_0=680 °C, P_0=30 MPa, to increase the unit efficiency by ~11% (relative). At the same time, in this variant, the thermal scheme becomes much more complicated with a simultaneous significant increase in the auxiliary power consumption of the unit.

4. The performed analysis of different variants for converting 300 MW power units produced by JSC "Turboatom" into USC ones allows us to choose the most rational modernization variant. The variant, which from the point of view of the authors, can be considered for further detailed studies, is the reconstruction of the HPC by converting it into a USCHPC capable of operating at the initial t_0=650 °C, P_0=30 MPa steam parameters and the addition to the IPC of an AIPC capable of operating at t_0=650 °C, P_0=6.957 MPa steam inlet parameters, provided the original IPC and LPH designs remain unchanged. This allows increasing the unit efficiency by ~7% (relative).

Acknowledgement

The work was carried out within the target program of scientific research of the National Academy of Sciences of Ukraine "Intellectual environmentally safe energy with traditional and renewable energy sources" ("New energy") for 2019–2021.

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Received 29 October 2021

Принципові рішення з модернізації енергоблоку 300 МВт при його переведенні на супернадкритичні параметри пари

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Проаналізовано стан енергетики України та основні тенденції розвитку світового ринку в області переведення потужних енергоблоків ТЕС на супернадкритичні параметри пари. Показано, що енергетика України потребує особливої уваги та впровадження нових сучасних технічних рішень. Світові тенденції говорять про те, що на цей час акценти робляться у напряму підвищення параметрів пари перед турбіною до супернадкритичних. Це дозволяє як підвищити ефективність енергоблоків, так і зменшити теплові викиди, тим самим вирішуючи глобальну екологічну проблему потепління клімату. Реалізація цього підходу пропонується з урахуванням

ванням реалій економіки України та наявних технічних можливостей енергомашинобудівної галузі. В роботі наведені результати варіаційних розрахункових досліджень теплової схеми енергоблоку потужністю 300 МВт при переведенні турбіни К-300-23,5 на супернадкритичні параметри пари. Завдання вирішувалося за умови максимального збереження теплової схеми, підвищення ефективності енергоблоку та мінімізації капітальних вкладень при модернізації турбіни. Вибір зупинено на збереженні системи регенерації, циліндрів середнього та низького тиску. Проаналізовано варіанти з доповненням існуючої турбіни циліндром на супернадкритичних параметрах пари та створенням нового циліндра високого тиску за незначних змін його габаритних характеристик. Результати досліджень показали, що найбільш раціональним варіантом модернізації турбоустановки електричною потужністю 300 МВт є створення нового циліндра високого тиску, який розраховано на роботу за супернадкритичних параметрів пари, а також доповнення циліндра середнього тиску новим циліндром з метою збільшення параметрів промперегріву пари при збереженні системи регенерації.

Ключові слова: *паротурбінний цикл, супернадкритичні параметри пари, теплова схема, енергоблок, моделювання, ефективність, математична модель, програмний комплекс, тиск, температура, модернізація, генерація.*

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DOI: https://doi.org/10.15407/pmach2021.04.049

UDC 539. 3

VIBRATIONS OF A CYLINDRICAL SANDWICH SHELL WITH A HONEYCOMB CORE MADE USING FDM TECHNOLOGY

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Presented is a model of the dynamic deformation of a three-layer cylindrical shell with a honeycomb core, manufactured by fused deposition modeling (FDM), and skins reinforced with oriented carbon nano-tubes (CNT). A ULTEM 9085 thermoplastic-based honeycomb core is considered. To analyze the stress-strain state of the honeycomb core, a finite element homogenization procedure was used. As a result of this procedure, the dynamic response of the honeycomb core is modeled by a homogeneous orthotropic material, whose mechanical properties correspond to those of the core. The proposed model is based on the high-order theory, extended for the analysis of sandwich structures. The skin displacement projections are expanded along the transverse coordinate up to quadratic terms. The honeycomb core displacement projections are expanded along the transverse coordinate up to cubic terms. To ensure the integrity of the structure, shell displacement continuity conditions at the junction of the layers are used. The investigation of linear vibrations of the shell is carried out using the Rayleigh-Ritz method. For its application, the potential and kinetic energies of the structure are derived. Considered are the natural frequencies and modes of vibrations of a one-side clamped cylindrical sandwich shell. The dependence of the forms and frequencies of vibrations on the honeycomb core thickness and the direction of reinforcement of the shell skins have been investigated. It was found that the eigenforms of a sandwich shell are characterized by a smaller number of waves in the circumferential direction, as well as a much earlier appearance of axisymmetric forms. This means that when analyzing the resonant vibrations of a sandwich shell, it is necessary to take into account axisymmetric shapes. Changing the direction of reinforcement of the skins with CNTs makes it possible to significantly influence the frequencies of the natural vibrations of the shell, which are characterized by a nonzero number of waves in the circumferential direction. It was found that this parameter does not affect the frequencies of the axisymmetric shapes of the shell under consideration.

Keywords: *cylindrical sandwich shell, additive technologies, honeycomb core, nano-composite skin, eigenforms, axisymmetric vibration mode.*
